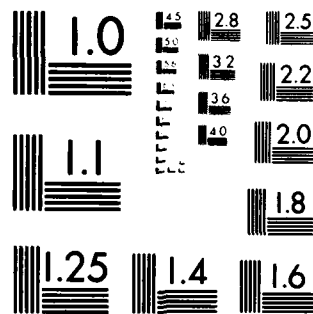


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FOREWORD

This report summarizes the results of a workshop held on the subject, Contact Damage in Ceramic Materials at Elevated Temperatures, at the National Bureau of Standards on January 21-22, 1982. The object of the Workshop was to assess the current state of understanding of contact phenomenon in ceramic materials and to identify likely areas of research for future studies. This report contains a summary of the meeting, suggestions for future study and a list of abstracts provided by the individual authors.



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SUMMARY OF THE PROCEEDINGS OF THE ONR/NBS WORKSHOP:

CONTACT DAMAGE IN CERAMIC MATERIALS AT ELEVATED TEMPERATURES

The objectives of the ONR/NBS Workshop on "Contact Damage in Ceramic Materials at Elevated Temperatures" included: (1) an assessment of the state of scientific understanding of contact phenomena in ceramic materials and (2) the identification of those areas of research within the discipline that look most promising for future study. Held at the National Bureau of Standards, January 21-22, 1982, the Workshop was attended by approximately 40 scientists and engineers who were actively involved in research on contact phenomena. As indicated in the attached agenda of the workshop, 14 formal lectures were presented to the attendees. Short abstracts of most of these lectures are included in this report. In order to cover both fundamental and practical aspects of the contact problem, the meeting was organized into four general areas of discussion: (1) practical problems encountered in heat engine programs; (2) strength degradation due to contact processes; (3) fundamentals of chemical and physical interactions of interfaces; (4) related tribological processes. This summary is divided into these same general areas of discussion. Recommendations for future research are presented at the end of the summary.

Contact induced strength degradation was identified by Richerson (Garret Turbine Engine Company) as a primary cause of the mechanical failure of turbine engines constructed of ceramic materials (reaction bonded Si_3N_4). Strength degradation is most severe at contact interfaces between the static components of turbine engines, and is the result of mechanical and thermal loading during engine operation. As the engine is heated from room temperature to the operating temperature, thermal expansion of the components results in sliding motion at the points of contact. If normal stresses at the contact sites are of a sufficient magnitude then sliding causes cracks to form at the contact sites, severely reducing the strength of the ceramic components. Mechanical damage appears to be more severe at temperatures in excess of $\sim 2200^\circ\text{F}$ ($\sim 1200^\circ\text{C}$) where most failures have occurred in operating turbine systems. Results presented by Fisher (Ford Motor Co.) support the findings of Richerson. Fisher emphasizes the importance of sticking of component parts at elevated temperatures as a cause of strength degradation.

The type of loading that occurs at contact sites has been modelled both theoretically and experimentally to determine the best design to eliminate contact problems in turbine engines. Experimental modelling is accomplished through the study of friction at elevated temperatures. The equipment used in this type of study simulates the sliding that occurs at contact sites in heat engines, but permits the investigator to vary the test conditions over a wider range of conditions than is experienced in practice. In this type of experiment, the temperature, the normal load, the radius of curvature at the contact site, and the rate of tangential displacement can all be varied independently, permitting the most important elements of the process to be identified relatively quickly. Experiments of this type were presented at the Workshop by Richerson on reaction bonded Si_3N_4 and sintered α SiC , and

by Wiederhorn (National Bureau of Standards) and Nadeau (University of British Columbia) on soda-lime-silica glass.

Richerson showed that the strength degradation required sliding in combination with normal loading for strength degradation to occur. Normal loading by itself does not reduce the strength of the components. The degree of strength loss was greater at 1100 °C than at room temperature. The strength loss was concomitant with an increase in the coefficient of friction as the temperature increased. The coefficients of friction for both the Si_3N_4 and the SiC increased from ~.2-.3 at room temperature to ~0.7-.8 at 1100 °C, while the strength decreased by a factor of ~2 for the same temperature range. Richerson attributes the behavior of the Si_3N_4 and SiC to the formation of a glassy coat on these materials at elevated temperatures, which results in either enhanced adhesion between the ceramic components, or the formation of a viscous phase at the contact sites, both of which can increase the surface adhesion forces. Thus, the glass and not the underlying ceramic probably controls the degree of surface stressing during sliding.

Wiederhorn and Nadeau presented their studies on soda-lime-silica glass, a 70% lead glass, silica glass, and aluminum oxide. The coefficient of friction for the lead glass and the soda-lime-silica glass increased from a value of ~.3 at temperature 200 °C below the fictive temperature to ~1 at a temperature close to the annealing temperature of the glass. For the other materials, which have a higher temperature for viscous flow, the coefficient of friction remained constant to 600 °C, the temperature limit of the study. Studies of glass spheres sliding on glass plates showed that the size of cracks formed in the glass surface was related to the static coefficient of friction. The larger the value of the friction, the larger the crack that was formed, and presumably, the lower the strength.

Models of fracture in contact situations were presented by Evans (University of California, Berkeley) and by Lawn (National Bureau of Standards). Evans considered the condition for crack initiation under a sphere that was subject to both normal and tangential forces. Tangential forces acting on an elastic contact area decreased the fracture initiation threshold dramatically. Evans' findings were consistent with the results of an earlier model by Lawn, and with the numerical analysis presented at the Workshop by Richerson. Evans noted that the threshold load for fracture depends on the properties of the materials in contact. Specifically, he predicts that materials with high toughness, low elastic modulus, and low Poisson's ratio are most resistant to strength degradation. Attainment of maximum toughness of structural ceramics appears to be central to the successful use of ceramics in contact situations.

The theory presented by Lawn dealt with the strength of ceramic components after they have been damaged in contact situations. Lawn emphasized the importance of residual stresses to the strength of components that are susceptible to subcritical crack growth. He notes that residual stresses introduced by contact processes can dominate the static fatigue behavior of the ceramic materials. If normal strength measurement techniques are used to characterize the static fatigue

behavior, then large errors can result when predictions of lifetime are made. In his talk, Lawn developed a method of handling static fatigue data so as to include effects of residual stresses and thus avoid errors of analysis that might creep into predictions of component lifetime.

Buckley (NASA), Rabinowicz (MIT) and Cannon (MIT) discussed the chemical and physical processes that dominate contact situations. From the discussion presented at the meeting on contact damage, it was clear that one of the important (perhaps the primary) determinants of strength degradation are the static and dynamic coefficients of friction that characterize the resistance to relative motion of components in contact. The coefficient of friction for materials is determined in a complex way by the chemical affinity of the slider and the test-plate towards one another and the plastic and elastic properties of these two parts. Plowing of the slider through the surface of the test plate may contribute significantly to the coefficient of friction when the slider is harder than the test plate. Normally, however, static and dynamic friction is believed to be controlled by physical and chemical processes that occur between contact asperities that characterize the junction between the test plate and the slider. The actual area of contact is determined by the area of contact at the asperities, and is actually only a small portion of the apparent contact area. Hence, processes such as plastic flow or sintering at the contact asperities can contribute to the coefficient of friction at a contact junction.

In his presentation, Buckley discussed the type of phenomena that had to be considered to understand the dependence of the friction on the physical and chemical properties of the materials that form the contact junction. He noted that the chemical and physical phenomena that occur can be quite subtle. For example, if silicon carbide, a hard abrasive material, is rubbed against iron in vacuum, the sliding coefficient of friction is relatively high, ~ 0.8 , at room temperature, primarily the result of ploughing of the SiC through the metal. At about 800°C , however, the SiC undergoes a graphite-forming, chemical decomposition at the contact surface, thus reducing the friction coefficient to ~ 0.3 as a result of graphite formation. A number of other examples illustrating the subtle nature of interactions at contact interfaces were also given by Buckley at the meeting. Buckley illustrated the use of surface analytic tools such as low energy electron diffraction, x-ray photo electron spectroscopy, scanning electron microscopy, auger electron spectroscopy, and field ion microscopy as methods of characterizing tribological surfaces to atomic detail. These tools can be used to obtain insight into both the nature of the deformation and the chemical reactions that occur at contact asperities. They are also useful for evaluating the nature and behavior of lubricants, which prevent surfaces from sticking during sliding.

In his talk on high temperature sliding, Rabinowicz emphasized the chemical nature of the contact surfaces and the importance of phase transformations to friction and wear. The wear of metals depends strongly on the structure of the metals used for the slider and the test plate. When the slider and test plate are identical high wear rates are obtained, whereas when the slider and test plate are chemically incompatible, low wear rates are obtained. Hence, the higher the

chemical affinity of two metals the greater will be the degree of wear when the metals are rubbed together. Rabinowicz suggests that similar relations should hold for ceramic materials; however, he notes that these relations have not yet been determined for ceramics.

Rabinowicz also noted that structural changes during sliding influence the friction and wear behavior of materials. Changes in crystal structure, the formation of surface films and the desorption of liquid lubricants can cause the friction coefficient to increase by a factor of two and the wear rate by a factor of 10. Thus, when stainless steel slides on boron carbide, the friction coefficient increases from ~.3 at 1000 °F (540 °C), to ~1, at 1200 °F (650 °C), and then decrease to ~.1 at 1500 °F (815 °C). Thus, the B_2O_3 coat that forms on the B_4C_3 acts as a lubricant at temperatures in excess of 1500 °C, but causes sticking at ~1200 °C. This same type of behavior is also observed at elevated temperatures for SiC, and will undoubtedly be important for contact situation in heat engines.

The importance of sintering to contact induced strength degradation was discussed by Cannon. Since the coefficient of friction is determined in part by the real area of contact between slider and specimen plate, any process that enhances the area of contact will also enhance the friction, especially when sliding is initiated. Normally, when two surfaces are in contact, but are free from external pressure, sintering is driven only by the surface tension of the solids at the contact asperities. The rate of sintering can be accelerated either by the application of an external stress or by the presence of a liquid at the interface: the external stress increases the driving force for sintering, the liquid provides an easier path for material transport. Since the times of densification are inversely proportional to the cube of the grain size, asperity dimensions will be important to the contact area formed as a result of sintering: the smaller the size of the asperities, the more rapid the sintering. Finally, high temperature liquids will be useful as lubricants, only if they do not enhance the rate of sintering between the two surfaces in contact. This conclusion is consistent with the comment by Buckley that good lubricants prevent adhesion at contact surfaces.

The talks by Hannoosh (Norton Co.), West and Signiuta (Advanced Mech. Tech. Inc.), and Yonushonis (SKF Industries) dealt with tribological behavior of ceramics. Hannoosh's talk dealt with the direct bonding of ceramics to metals and the types of stresses that are expected to arise as a result of thermo-elastic mismatch at contact interfaces. A simple bimaterial model was given to illustrate the role of thermal expansion and interfacial contact angle on the bonding of SiC to metals. Considerations of this type will be important in evaluating the stresses that occur where ceramic components are joined to metallic components in heat engines.

West presented the results of a pin-on-disk evaluation of ceramics intended for use in stationary diesel engines. Studies were conducted in air at room temperature, 400 °F (204 °C), 600 °F (315 °C) and 800 °F (427 °C). More than 30 different ceramic materials were evaluated. Wear rates were determined by weight loss measurement; wear surfaces

were characterized by scanning electron microscopy procedures. As a result of the study, the following conclusions were reached: (1) sintered materials behaved better in a wear situation than the hot pressed materials, suggesting that small flaws improve the wear behavior of ceramic materials; (2) no simple correlation between wear rate and material properties was obtained; (3) the correlation between the coefficient of friction and the hardness was poor ($r \sim -0.5$); (4) wide variations were obtained for the friction and wear behavior of ostensibly the same type of materials made by different manufacturers; (5) oxidation could be used to modify the friction and wear behavior as a function of temperature, and to create a solid lubricant at the contact interface. Although the talk by West demonstrated the diverse behavior of non-oxide ceramics in sliding contact, justification of tribological behavior in terms of chemistry and microstructure were not given. From the talk it was clear that a considerable amount of additional work will be needed to relate tribological behavior to chemical composition and microstructure of the materials studied.

The talk given by Yonushonis dealt with solid lubrication of bearings made of hot-pressed silicon nitride. These bearings were designed for applications at high temperatures. Tests showed that graphite films were effective in preventing silicon nitride wear at temperatures as high as 1000 °F (540 °C). Low wear rates were obtained with Pure Carbon P2003 as lubricant, other lubricants (WSe_2 -In-Ga composites, MoS_2 films, WS_2 films) were not as effective in preventing wear. Since breakdown of the lubricants occurred at 1200 °F (650 °C) additional research will be needed to identify lubricants that can operate at higher temperatures. With regard to turbine applications and the contact problems addressed by the Workshop, the need for research is apparent if lubricants that can operate at turbine engines temperatures are to be developed.

Short talks were presented to the meeting by C. S. Yust (Oak Ridge National Laboratory) and by C. M. Wu and R. W. Rice (Naval Research Laboratory). Yust recommended the technique of transmission electron microscopy as a method for understanding the type of damage that occurs along wear tracks during sliding. This technique was developed and used successfully by B. J. Hockey (National Bureau of Standards) to characterize surface damage resulting from erosion and surface abrasion of ceramic materials and Yust noted that the technique should also be applicable for studies of surface wear. Yust also noted that surface properties could be enhanced by ion implantation, and presented experimental data to support his suggestion. Wu and Rice presented data relevant to the effect of microstructure on the wear of ceramic materials. They showed that the wear rate of Al_2O_3 increased as the grain size increased, primarily as the result of intergranular microfractures. They also found that the wear rate could be related to the porosity of their specimens, the wear rate decreasing as the porosity increased. This finding is consistent with the observation reported at the Workshop by West and Signiuta.

RECOMMENDED AREAS FOR RESEARCH ON CONTACT INDUCED STRENGTH DEGRADATION

Based on discussions at the Workshop several areas of research seemed most important to the development of an understanding of strength degradation in contact situations. These may be roughly divided into three categories: (1) the mechanics of strength degradation; (2) the physical-chemistry of contact interfaces; and (3) the importance of material microstructure to strength degradation. Each of these areas of research are discussed briefly below.

Mechanics of Strength Degradation: Current models of strength degradation predict the initiation condition for crack growth. Experimental data to check these theories are lacking at elevated temperatures. Additional modelling is needed to predict the maximum extent of crack growth during sliding and the degree of strength loss resulting from the crack growth. Experimental data and theoretical modelling of localized cyclic loading (fretting) are needed to develop an understanding of the effect of cyclic loads on strength. The importance of elastic-plastic deformation to strength degradation should be investigated. Finally, loading rate effects, and effects of environment on contact damage have yet to be examined in any systematic manner.

Physical Chemistry of Contact: As was evident from discussions of strength degradation, the physico-chemical processes that occur at contact interfaces control both the level of friction between two components. To better understand the nature of these processes, the concepts and techniques used in metal tribology should be applied to ceramics. Surface analytical techniques should be used to define the types of chemical reactions that occur at interfaces. Ideas of chemical affinity should be used to evaluate those contact pairs that are least likely to react in a contact situation. A prime object of the physico-chemical research should be the reduction of friction at contact interfaces, which may be accomplished both through the use of less interactive materials, and the development of high temperature lubricants (perhaps metals) to prevent adhesion at surfaces of contact.

Material Microstructure: The microstructural parameters that are most important in reducing the mechanical damage from sliding should be identified. Systematic investigations of the effect of grain size and porosity on strength degradation should be conducted. Methods of surface modification (chemical vapor deposition or perhaps ion implantation) should be investigated with the object of developing surfaces that are resistant to strength degradation.

ONR-NBS Workshop

Final Program

Contact Damage in Ceramic Materials at Elevated Temperatures

**NBS (Lecture Room B)
Gaithersburg, MD
January 21-22, 1982**

Thursday, January 21 - Morning Session

9:00 - 9:20	D. W. Richerson - AiResearch Contact Damage in Ceramic Turbine Components
9:30 - 10:00	E. A. Fisher - Ford Ceramic Turbine Component Interfaces
10:10 - 10:50	D. H. Buckley - NASA Adhesion, Friction and Wear Processes in Solid State Contact
11:00 - 11:15	Break
11:15 - 11:55	E. Rabinowicz - MIT High Temperature Sliding
12:05 - 12:35	R. M. Cannon, Jr. - MIT Contact Sintering
12:45 - 1:45	Lunch

Afternoon Session

2:00 - 2:30	A. G. Evans - University of California at Berkeley Strength Degradation
2:40 - 3:10	B. R. Lawn - NBS Fatigue in Contact Problems
3:20 - 3:50	D. W. Richerson - AiResearch High Temperature Studies of Interface Friction and Contact Stress in Silicon Nitride and Silicon Carbide
4:00 - 4:30	S. M. Wiederhorn - NBS J. S. Nadeau - University of British Columbia Friction and Strength Degradation in Vitreous Systems
5:20	Adjourn

Friday, January 22 - Morning Session

9:00 - 9:30	A. W. Metcalfe - Solar Glass-Based Adhesives for Joining Ceramics
9:40 - 10:10	W. Signiuta - AMT High Temperature Friction and Wear
10:20 - 10:50	T. M. Yonushonis - SKF Solid Lubrication of Bearings
11:00 - 11:15	Break
11:15 - 1:00	Short Presentations, Discussion
1:00 - 2:00	Lunch

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January 21-22, 1982

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ABSTRACTS

CONTACT DAMAGE IN CERAMIC TURBINE COMPONENTS--HIGH TEMPERATURE
STUDIES OF INTERFACE FRICTION AND CONTACT STRESS

D. W. Richerson

Garrett Turbine Engine Company

Contact stress was identified during the DARPA/NAVY/Garrett Ceramic Gas Turbine Engine Demonstration Program as a critical source of damage or fracture of ceramic engine hardware[1]. Three contact stress fracture modes were encountered during engine testing and subsequently studied experimentally and analytically: (1) impact; (2) contact/vibration; (3) interface biaxial loading. Interface biaxial loading was the most critical and will be discussed in the following paragraphs.

The stress distributions for normal and biaxial loading have been evaluated analytically[2-6] and the fracture mechanisms studied analytically and experimentally[7-10]. As shown in Figure 1, the stress under normal contact loading is essentially compressive, whereas for biaxial or sliding loading, a high tensile stress spike is present at the trailing edge of the contact surface. The severity of the tensile stress is dependent upon the magnitude of the normal load, the contact geometry and the interface elastic friction.

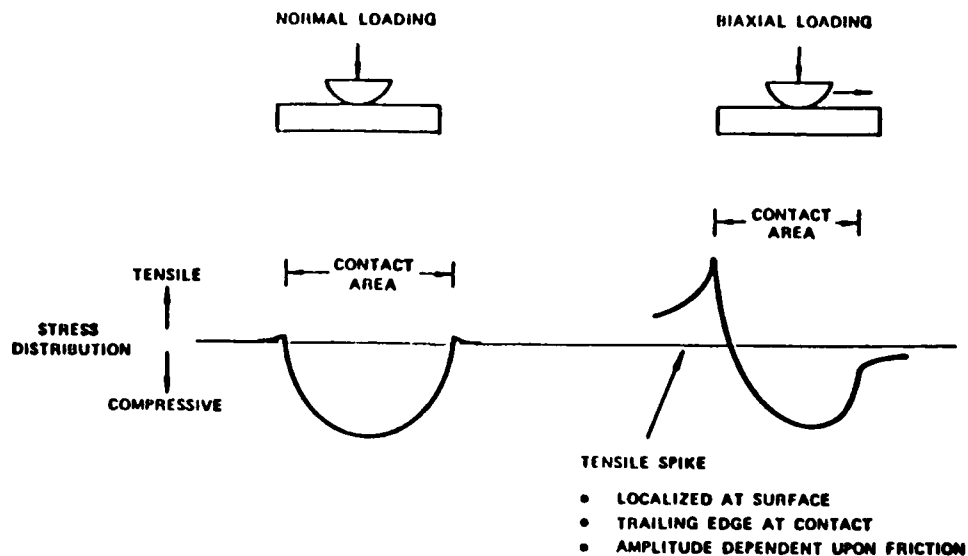


Figure 1. Schematic of Stress Distributions Resulting from Uniaxial and Biaxial Loading at a Contact Surface.

Contact damage occurred in the DARPA/NAVY engine at interfaces between reaction-bonded Si_3N_4 (RBSN) static structure components. Although the engine had been initially designed to carry aerodynamic contact loads in compression, several potential sources of localized biaxial loading were identified during the program:

1. Accumulated tolerance mismatch, resulting in tilting of some ceramic components to produce a non-normal contact load path. The design, which provided firm support at the OD but allowed the ID some freedom to float, increased the likelihood of tilt.
2. Differences in temperature response between adjacent components, resulting in sliding in the radial direction due to thermal expansion differences.

A study was conducted under the program to evaluate the sensitivity of RBSN to contact stress[11]. Normal and biaxial loading were examined for a contact area of approximately 700 by 350 μm . Normal loads up to 140 kg were applied at 1100 °C with no damage (as determined by subsequent strength testing). However, for sliding contact at 1100 °C, visible surface damage with strength reduction to less than half the baseline strength occurred for normal loads as low as 10 kg. The breakaway coefficient of friction measured for the RBSN during the sliding tests was 0.8. Use of a particulate ceramic lubricant reduced the coefficient of friction to 0.2 and substantially reduced the contact damage and strength loss.

Contact testing was conducted for point contact and for line contact for RBSN and for sintered αSiC at temperatures ranging from room temperature to 100 °C[12,13]. The coefficient of friction was higher for both materials at elevated temperature, especially for the line contact geometry. Room temperature line contact values ranged from 0.2 to 0.3 compared to 100 °C values of 0.7. Experimental data to date suggests that the increase in friction is due to the presence of a glassy silicate surface layer (present from oxidation of the Si_3N_4 or SiC) which either increases adhesion or produces viscous drag. The increase in friction associated with this glassy surface layer does not result in a corresponding increase in surface tensile stress. Studies are continuing in an effort to better understand the factors affecting high temperature interface stresses and to separate the elastic effects from the viscous (or other) effects so that analytical predictions are possible.

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CERAMIC TURBINE COMPONENT INTERFACES

E. A. Fisher

Ford Motor Company

During three years of operation, over 2500 hours of testing has been accumulated on structural ceramic turbine components in the Ford Flowpath Test Rig. This testing, over a highly transient duty cycle at temperatures up to 2500 °F, has provided experience with ceramic interface contacts between Si_3N_4 - Si_3N_4 , Si_3N_4 - SiC, and SiC - SiC components. Interface design considerations of the various structural components are discussed. While no evidence of fretting damage was uncovered during this testing, component sticking did result in failures. Testing procedures are reviewed which minimized the effect of this sticking and permitted the attainment of up to 500 hours of durability on individual components.

ADHESION, FRICTION AND WEAR PROCESSES IN SOLID STATE CONTACT
D. H. Buckley
National Aeronautics and Space Administration

The tribological surface is described with respect to physical profile, crystallinity and surface chemistry. The surface topography of most real surfaces is discussed as well as the asperity free surface which can be generated under certain selected conditions. The presence of crystallinity in materials can effect through variations in orientation the surface topography.

There are many surface events which are shown to effect tribological behavior. These include such events as surface reconstruction, segregation, chemisorption and compound formation. Each of these events produces an effect upon adhesion, friction and wear. Frequently minor changes in, for example, surface chemistry will bring about pronounced effects upon such properties as adhesion and friction. Fractions of monolayers of chemisorbed species such as oxygen or chlorine on surfaces reduce static friction forces.

Surface films are shown to also effect near surface or surficial mechanical properties. The presence of oxides on metals can produce a surface hardening while water and organic molecular structures can result in surface softening. These surface film related mechanical properties effect friction and wear.

The development of surface analytical tools has made it possible to very carefully characterize a tribological surface even to atomic detail with such devices as the field ion microscope with the atom probe. Some of the tools that have been used to characterize tribological surfaces include, LEED (low energy electron diffraction), XPS (x-ray photoelectron spectroscopy), SEM (scanning electron microscopy with energy dispersion x-ray analysis), Auger electron spectroscopy, the field ion microscope with the atom probe attached thereto and other techniques. Friction, adhesion, wear or lubrication experiments have been conducted in devices incorporating many of these instruments for in situ analysis of surface, before, during and after completion of tribological experiments.

The environment and the films found on solid surfaces from an interaction of the environment with those surfaces are shown to strongly influence adhesion, friction, and wear. In some instances these films can completely dominate tribological performance. For example, oxygen can completely displace a sulfide anti-wear film and even solid lubricants are shown to depend on the environment for their performance.

With solid state interactions adhesion is found to be related to the cohesive binding energy. The interfacial bonds developed between the two surfaces are shown to be stronger than the cohesive bonds in the cohesively weaker of the two materials. Strong adhesive bonding is observed to occur for metals in contact with ceramics, semiconductors, carbons and polymers. Bond strength at the interface is, with some exceptions, stronger than the bond strength of the cohesively weaker of the two materials.

The adhesive bonding of metal to ceramics such as aluminum oxide relate to the ability of the metals to form stable oxides. Those metals that do form stable oxides exhibit higher friction and wear than those that do not, such as gold.

With glasses adhesion and friction is greater for the glasses in contact with themselves and metals in the presence of moisture than its absence. Thus, while for metals in contact with themselves adhesive bonding is stronger in the absence rather than the presence of surface contaminants, at least for glasses, bonding is stronger in the presence of moisture than in its absence.

Strong interfacial bonding is observed to occur for metals to semiconductor surfaces. For example, gold bonds very strongly to silicon with gold transferring to the silicon surface on simple touch contact. This happens in the absence of any type of solid solubility between these materials.

Metals contacting carbon materials such as pyrolytic graphite manifest a strong orientation dependence. Binding of metals and adhesive transfer occurs very strongly to the prismatic orientation while only weakly to the based surface orientation. The diamond form of carbon exhibits strong bonding even on the natural (111) cleavage surface to metals. The friction of the metals in contact with diamond is related to the percent d character of the metal bond. The greater the percent d character the lower the friction.

Many different surface properties influence tribological performance. High surface energy correlates with strong adhesion and high friction. Crystallographic orientation influences behavior; the atomic density, low surface energy planes have lower friction and experience less wear than do low atomic density planes. This agrees with surface energy observations since the high atomic density crystal planes are also the low surface energy planes.

Friction and wear are lower for amorphous alloys than they are for those same alloys in the crystalline state. Metallic glasses are of considerable tribological interest because they are as hard as steels, yet have substantial plasticity, are tough and are among the strongest of engineering materials.

Friction studies with metallic glasses over a range of temperatures indicate an increase in the friction properties with the transformation and further increases in temperature results in surface segregation of species such as boron and nitrogen resulting in the formation on the surface of boron nitride. This material has inherently low friction and wear and accordingly these properties are markedly reduced.

Thin adsorbed surface films markedly alter the tribological properties of materials such as magnesium oxide. For example, adsorbed films containing chloride ions result in the formation at the surface of magnesium chloride and the diffusion of the chlorine into the magnesium oxide to a sufficient depth so as to produce a change in surface microhardness and accordingly friction and wear. X-ray photoelectron

spectroscopy and in depth profile analysis followed the chloride ion diffusion into the bulk material.

Studies with silicon carbide and silicon nitride as a bearing material for use at elevated temperatures has revealed the extreme importance with compounds of temperature effects. With silicon carbide, x-ray photoelectron spectroscopy, Auger spectroscopy and low energy electron diffraction have revealed that a type of surface reconstruction occurs in vacuum with temperature. This event has a pronounced effect on tribological properties. At about 800 °C the carbon to silicon bond undergoes session with subsequent evaporation of the silicon with further temperature increases. The carbon remaining on the surface collapses into a pseudo-graphitic structure which then acts as an effective solid lubricant film. At 1500 °C the friction coefficient is near the boundary lubrication regime.

HIGH TEMPERATURE SLIDING

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The basic relationships for the friction and the adhesive wear of sliding solids are presented, and it is shown that, in general, the friction and wear coefficients are not very dependent on the ambient temperature, almost up to the melting temperature. This implies that the volumetric wear rate, which is inversely proportional to the hardness, increases a function of the temperature, and so does the size of adhesive wear debris. Illustrations of these effects are provided.

Various complications can arise when there is marked frictional heating, leaving a soft surface layer on a hard substrate. This reduces the friction, but generally the wear rate becomes larger. The literature contains some disagreement on the exact nature of these 'melt lubrications' effects, and widely varying friction coefficient value have been reported.

In special circumstances the friction and wear can change drastically over a narrow temperature range, generally called a transition temperature. Change in crystal structure, the formation of surface films of sufficient thickness by chemical reaction with the environment, and the desorption of liquid lubricants from the sliding surfaces are some of the best established of the phenomena which lead to transitions. Typically, a transition changes the friction by a factor of two and the wear by a factor of ten, although much larger changes are sometimes observed. These transition effects are illustrated, and the opportunities and dangers associated with the use of these effects in practical sliding systems are discussed.

Most of the experimental testing described in the literature has been carried out with metals, and they are characterized by high friction and wear coefficient values, high values of surface energy, and strong effects associated with the metallurgical compatibility or incompatibility of the two sliding surfaces. The resemblances and differences associated with the use of sliding ceramics are illustrated, and it is shown that transition phenomena and compatibility effects also occur with ceramics, but that the effects are generally less drastic. It should be noted that, since ceramics have very high melting temperatures, creep temperatures, etc., transition effects in ceramics often occur only at correspondingly high temperatures.

However, new phenomena can arise with ceramics. For example, since ceramics are subject to brittle fracture wear and brittleness effects are temperature dependent, it can easily happen that the wear rate drops as the temperature is increased.

It is often difficult to study the sliding behavior of ceramics because several techniques of investigation (e.g. using the electrical resistance at the interface, making the interface one junction of a thermocouple, using exoelectron emission to study new surface formation) are not generally available.

THE INFLUENCE OF A TANGENTIAL FORCE ON THE FRACTURE OF TWO
CONTACTING ELASTIC BODIES

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The problem of fracture initiation at two elastically contacting structural components, subject to applied normal and tangential forces, has been analyzed. The fracture initiation load has been predicted to depend sensitively upon the magnitude of the applied tangential force and the interfacial friction coefficient, and to exhibit important dependencies on the fracture toughness, elastic modulus and curvature of the contacting bodies. Experimental results obtained on glass and Si_3N_4 conform with the trends predicted by the analysis.

FATIGUE IN CONTACT PROBLEMS

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A theory is formulated for the general fatigue response of brittle flaws which experience residual stress concentrations. The indentation crack is taken as the model flaw system for the purpose of setting up the basic fracture mechanics equations, but the essential results are expected to have a wider range of applicability in the strength characterization of ceramics. A starting fatigue differential equation is first set up by combining an appropriate stress intensity factor for point- or line-contact flaws with a power-law crack velocity function. Analytical solutions are then obtained for the case of static fatigue. The resulting relation between lifetime and failure stress is shown to have exactly the same power-law form as the conventional solution for Griffith (residual-stress-free) flaws. This "equivalence" is used as a basis for extending the results to dynamic fatigue. A comparison of these analytical solutions with numerical counterparts from an earlier study defines the limits of accuracy of the theoretical procedure. However, while the form of the lifetime relation remains invariant, the values of the exponent and coefficient differ significantly for flaws with and without residual stress. Accordingly, the application of conventional fatigue to evaluate crack velocity parameters, without due regard for the nature of the critical flaw, can lead to serious errors. Explicit conversion formulae are given for transforming "apparent" velocity parameters for indentation flaws directly into "true" parameters. The implications of these results concerning the use of the indentation method for materials evaluation are discussed.

FRICTION AND STRENGTH DEGRADATION IN VITREOUS SYSTEMS

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A summary of research to elucidate our understanding of strength degradation as a result of contact phenomena is presented. Current theories of contact induced strength degradation are reviewed. These may be separated into the sharp contact configuration and the blunt contact configuration. Strength degradation as a result of contact phenomena in heat engines is most closely simulated by the blunt contact configuration first analyzed by Hertz for the situation of static loading. The Hertz analysis was generalized by Lawn to include fracture that occurs during both normal and tangential loads. Using the concepts of fracture mechanics Lawn developed equations that gave conditions for crack initiation from (1) the elastic constants and physical dimensions of the solids in contact, (2) the fracture toughness of the solids, (3) the size of the critical flaw in the surface of the solids, and (4) the coefficient of friction for sliding. Although the equations developed by Lawn do not predict the maximum size to which a crack will grow once it has been initiated, they do yield a set of parameters that can be tested experimentally for crack initiation. One object of the work presented in this paper is the collection of friction data and strength that could be correlated with the theory developed by Lawn.

Three sets of equipment were developed to measure the type of interactions that occur during sliding contact: a ball on plate apparatus; a plate on plate apparatus; and an adhesion apparatus. The ball on plate apparatus was built to measure friction and to characterize the type of damage that occurs in a situation that simulates contact processes in heat engines. The plate on plate apparatus was built to measure friction in a situation in which mechanical damage does not occur during sliding. The adhesion apparatus was developed to determine the range of temperatures over which significant adhesion occurs when a sphere is loaded normally onto a flat plate. All of the equipment was capable of operating at temperatures as high as 800 °C. Glass plates and spheres were the primary objects of study during the initial stages of our investigation.

Results from the plate apparatus indicate that the coefficient of friction of between two solids increases dramatically as temperatures are increased to levels at which atomic motion can occur easily. For soda-lime-silica glass and a 70 percent lead-silica glass, the coefficient of friction was constant, ~0.3, from room temperature to about 200 °C below the fictive temperature. As the temperature increased the coefficient of friction increased to ~1 at the fictive temperature of the glass. Similar studies on silica glass, and aluminum oxide, which have much higher temperatures for atom mobility, give no indication of an increase in the friction coefficient.

Studies using glass spheres on soda-lime-silica glass indicated a similar increase in the coefficient of friction at about 200 °C below the fictive temperature of the glass. This increase in the friction

coefficient could not be attributed to adhesion effects as measured by the normal loading of a sphere on a plate, since adhesion does not occur for soda-lime-silica glass until the temperature exceeds the fictive temperature of the glass. Apparently tangential as well as normal forces are needed for the observed effect.

Examination of wear tracks on the soda-lime-silica glass indicate that plastic flow occurs at all temperatures when glass slides upon glass. As the temperature is increased the zone of plastic flow is observed to increase and the friction seems to arise primarily from plowing of the sphere through the glass plate. At elevated temperatures crack formation is most severe at the point where sliding initiates and can be correlated with the higher frictional forces required to initiate motion of the slider. Near the fictive temperature large cracks are observed at the start of the wear track, however, little or no cracking is observed along the actual wear track. By contrast, crack formation is much more uniform along the wear track at room temperature. The relevance of the crack formation to the strength of the glass has not yet been established.

A MECHANICS APPROACH TO CERAMIC TO METAL BONDING
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The ability to successfully bond ceramic materials directly to metals is necessary if ceramic materials are to be used successfully as structural components. For this reason, several ceramics manufacturers presently have internally funded development programs on ceramic to metal bonding.

This paper describes mechanics approaches to the determination of the stress states and singularities at a ceramics/metal interface. The stress states are shown to be functions of the coefficient of thermal expansion differences, elastic moduli differences, temperature change and geometry of the components to be bonded. The singularities that exist at the interface have been shown to be functions of the elastic moduli and Poisson's ratio differences and the interfacial contact angle of the two components.

Graphical results of a simple elastic bimaterial model will be given showing the role of the above-mentioned variables for SiC bonded to metals. Methods of solution using finite element analysis and fracture mechanics will be outlined. Successful brazing of SiC to refractory metals will be discussed.

TRIBOLOGICAL ASSESSMENT OF CERAMIC MATERIALS

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A pin-on disk friction and wear test apparatus was developed for the screening of ceramic materials which could be incorporated into the design of stationary diesel engines. The cylinder liner and top piston ring of diesel engines typically see maximum temperatures of 400 °F; consequently, tests were run at ambient, 400°, 600°, and 800° F in air. More than 30 different ceramic materials were evaluated.

In addition to the tribology tests, the better materials were characterized by indentation techniques as to their hardness and fracture toughness. SEM and EDAX were used to examine the wear surfaces.

Some unexpected results were observed. Generally, sintered materials were more wear resistant than hot-pressed materials. Apparently, the presence of small flaws improves a material's wear properties.

No correlations could be found between the observed wear and the material properties for a given material. The presence of porosity, impurities, second phases, and processing techniques must also be considered.

The coefficient of friction appeared to be inversely proportional to the hardness, although this correlation was not definitive ($R=.51$).

There is wide variation in the friction and wear properties of a given material manufactured by different suppliers. Different sintering agents, powder purities, and processing techniques all affect a material's tribological properties.

Certain materials were observed to have oxidized at 600° and/or 1800° F. This oxide acted as a solid lubricant for some materials (e.g., TiC), while it also appeared to reduce the wear rate for a Si_3N_4 material that contained iron impurities (Kyocera's SN 501).

As a first step, materials were evaluated while running against themselves. Using the experience gained here to reduce the size of the testing matrix, dissimilar pairs are now being tested, as well as plasma and CVD coatings.

This work was supported by D.O.E. contract numbers DEAC0379ET15444 and DEAC1980BC10362 during the period August 1979-June 1981.

SOLID LUBRICATION OF CERAMIC BEARINGS

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Advancements in the performance of high speed turbomachinery require the rotating turbine components to operate at higher speeds and higher temperatures. The temperatures projected for the bearing locations of compact, limited life, high performance turbine engines exceed the capability of conventional lubrication systems and conventional metal bearing alloys. These high temperature bearing locations will require the development and use of a solid lubricated bearing.

SKF Industries with funding from the Air Force Materials Laboratory and the Naval Air Systems Command has been investigating a bearing quality ceramic, hot pressed silicon nitride (HPSN) which has the potential to operate at the arduous service conditions projected by engine manufacturers. Experimental programs have demonstrated that properly finished HPSN rolling elements have acceptable oil lubricated fatigue lives. These programs have also shown that HPSN can be effectively lubricated by graphite transfer films at temperature up to 1200 °F (650 °C).

Hot pressed silicon nitride has been selected for high temperature bearing applications due to the material's low thermal expansion coefficient, low density, high temperature strength, oxidation resistance, and superior rolling contact fatigue resistance. A review of oil lubricated ceramic bearing test results calls attention to the need for high quality ceramic material, adequate finishing procedures, and proper bearing design in order to realize the potential of ceramic bearings, for example, porosity or inclusions have been shown to decrease oil lubricated fatigue lives by as much as three orders of magnitude. These same inclusions or pore distributions would be expected to decrease the basic material flexure strength by 25%. The final surface preparation has a similar effect on fatigue life. Perfectly acceptable ceramic materials can fail prematurely in rolling contact fatigue tests when the surface preparation was inadequate. Refinishing the material can result in substantial improvements in bearing performance. In addition to the effects of material related and finished related defects on bearing performance, the critical nature of bearing design should be realized. Seemingly minor differences in bearing contact angle, misalignment, and the ratio of ball diameter to groove radius have a significant influence on the Hertzian contact stress and the bearing fatigue life.

The prediction of bearing fatigue lives, use, and understanding of high temperature solid lubricated bearing systems is in its infancy when compared to oil lubricated rolling contact bearings. Experimental programs at SKF have demonstrated that solid lubricant films can be transferred from the cage surface to the ball and ring surfaces. These tests have shown that graphite films were effective at preventing silicon nitride wear at 1000 °F (540 °C) in rolling contact. The lowest silicon nitride wear rates were achieved with a Pure Carbon P2003 graphite cage at the test conditions selected. The experiments revealed

that other graphite based materials, WSe_2 -In-Ga composites MoS_2 films, and WS_2 films were not as effective in preventing silicon nitride wear. Analysis of the test data revealed that the wear rate of P2003 graphite solid lubricated HPSN at 1000 °F (540 °C) was comparable to oil lubricated steel bearings at much lower temperatures.

Optical and SEM examinations of inadequately lubricated silicon nitride revealed microfissuring and microspalling in the wear track. Tests at 1200 °F (650 °C) were limited by the graphite capability and possibly the silicon nitride capability at the 400 ksi (2760 MPa) contact stress.

Additional research at higher temperatures is required once adequate solid lubricants are identified. In addition to basic research in solid lubrication, considerable expertise will be required to properly design and attach a solid lubricated ceramic bearing for high speed applications. The limited test results to date reveal a requirement for improved ceramic attachment concepts, solid lubricant cage designs, and higher temperature solid lubricant systems.

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MICROSTRUCTURAL DEPENDENCE OF CERAMIC WEAR

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The orientation and results of our wear program, initiated about two years ago, are outlined. The two tests now operation are a Pin-on-Disk (POD) and a commercial (Tabor) tester using two abrasive wheels wearing on a disk sample. The current program has focused on grain size and porosity dependence of wear. The longer range goal is to inter-relate the above two, and possibly other, tests to each other and to basic chemical-microstructure character of the samples. Much of the emphasis is expected to be on the mechanics of micro-fracture as a critical aspect of wear, with x-ray topography as a tool of particular interest.

Fine grain, hot pressed Al_2O_3 has been tested with the POD apparatus as a function of porosity (P). Wear (measured by the cross sectional area of the wear track) was found to reasonably fit an exponential dependence, i.e. e^{-bP} , where b is a constant, as for other mechanical properties. Data for different loads could be normalized by treating wear similar to hardness except the b value changed significantly at $P \sim 20\%$. At $P < 20\%$, b was ~ 3 , similar to most other mechanical properties, but changed to ~ 11 for $P > 20\%$. The latter is higher than the trend found for vickers hardness ($b \sim 6$).

Wear studies of dense Al_2O_3 bodies of varying grain size with both the POD and Taber testers show wear rates increasing with grain size. The POD test shows a greater increase of wear with grain size. SEM observations show microfracturing and resulting wear is on the scale of the grains, often intergranular especially in larger (e.g. $\sim 50 \mu\text{m}$) grain Al_2O_3 . The POD test is also being used to observe effects of closely approaching and crossing wear tracks (e.g. as found with the Tabor test) where enhanced microfracture is seen.

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